INTERSTELLAR METEORS

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ABSTRACT

Interstellar dust (ISD) particles larger than about 1 μm (4×10^{-12} g) can penetrate freely into the inner solar system where, in the event of Earth impact, they can be accessed by the detection of the plasma and excited species created when the particles ablate in the Earth's atmosphere. The ablation process and current experimental techniques available for plasma and excitation detection mean that the particle size regime accessible from ground-based sensing is much larger than can be sampled from space-craft. However, the much larger collecting area provided by the atmosphere in the meteor mode results in comparable detection statistics for the two techniques.

The value of this Earth based probing of interstellar dust lies in the ability to provide quality dynamical characteristics: the velocity information allows the recovery of the ISD pre-solar system encounter trajectories. This paper provides an overview of experimental techniques and the attempts to map the galactic sources of interstellar dust.

1. INTRODUCTION

The sampling of galactic interstellar dust particles ISD within the solar system is important because it has the potential to provide access to the mineralogy, thermal and isotopic history, dynamics and sources of dust within the local galactic environment.

Directional scattering of ISD will occur during their journey in the galaxy: close coupling to the local gas flow and the interstellar magnetic field will exist with scale-lengths ranging from ~ 1 pc for dust $\sim 1\,\mu$m to $\sim 10^3$ pc for $\sim 50\,\mu$m [1]: only for large grains will observed trajectories with respect to the local standard of rest directly reflect source locations. Modelling of the ejection mechanisms from astrophysical dusty environments are available [2].

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As complementary to current *in-situ* impact detections and collections, the meteor technique can offer more precise trajectory information and therefore possible source identifications of ISD. Because of different coupling scale-lengths we expect the small particles for *in-situ* detections to be coupled to the interstellar gas in the solar neighbourhood, while larger bodies yielding meteors will be uncoupled.

Interstellar dust entry into the solar system is mass filtered at the heliopause because of both the interaction of the charged dust with the solar magnetic field and solar radiation pressure. The precise mass-dependent filtering varies with solar conditions but only those particles with diameters greater than $\sim 2\mu$m can penetrate freely on near Kepler orbits into the inner solar system. It is the depleted population size less than about 1μm that is detected by vehicles like Ulysses or captured by the recent Stardust aerogel collections.

Employing the Earth's atmosphere as a collector and sensing via the generation of excitation and plasma resulting from meteoroid ablation provides a much larger sampling area than available via space missions: this is compensated by the much smaller (by a factor of $\sim 10^3$ in mass) particles that can be sampled by impact detectors (on e.g. Ulysses). Only particles larger (velocity and physical structure dependent) than about 5 μm reach sufficient temperature to release kinetic energy into excitation and ionisation. There will exist some cut-off in mass dictating whether very large particles – the ones corresponding e.g. to visual meteors – can be built in stellar atmospheres, protoplanetary disks or other galactic regions: an upper limit may exist to observable ISD masses.

An important goal of ISD studies is to delineate extra-solar dust sources: a ground-based system, while able to measure spatial trajectories to a greater accuracy than can be done from space vehicles, has the limitation of sampling in the ecliptic plane at 1 AU from the Sun and means the identification of ISD has to be accomplished in the presence of a rich density of foreground cometary and asteroidal dust of flux larger by several orders . For space vehicles like Ulysses with trajectories out of the ecliptic detection is not impeded by the local dust population.

For particles on Kepler trajectories and free of interactions with other solar system bodies (for comparison the Hills sphere of Jupiter has a diameter of 0.6 AU), at Earth impact near 1 AU open solar orbits correspond to heliocentric speeds of 41.4 to 42.8 kms^{-1} depending on solar longitude.

Meteors are valuable in seeking ISD on gravitationally unbound (open) orbits in the presence of the preponderance of bound (closed) orbits. Information on ISD employing their meteor signatures has been sought by several techniques.

2. METEOR DETECTION

2.1. Visual, photographic and electro-optical

In the particle mass range greater than approximately 1g in early (pre 1940) visual work, measurements were attempted of the atmospheric speed and the elongation of the upstream direction (apparent radiant) from the Earth's Apex – this provides an estimate of the heliocentric speed. Even with ingenious methods such as the rocking mirror technique to judge angular speed this proved difficult to achieve with sufficient accuracy (e.g. Harvard Arizona campaign [3]) resulting in an unrealistic picture of the unbound population.

The introduction of dual Baker-Super-Schmidt cameras with a few 10s of km spacing enabled orbits down to masses of $\sim 10^{-2}$g to be secured (for example [4]). Image intensifier and CCD systems have pushed the limiting mass down to 10^{-4}g ([5],[6],[7]). Many meteor groups, some affiliated to the International Meteor Organisation or to the IAU and some independent, are carrying out regular spaced camera surveys - like the Dutch, Finnish, and Japanese Meteor Societies and European network and other groups. Data catalogues from such campaigns are available (for example [8]) and form a valuable resource.

Analyses of these data yield extra-solar component of between 0.2% and 22% depending on the technique and statistical stringency employed. In these observations the flux provided was not sufficient to enable any coherent extra-solar inflow directions to be assessed with concern being focussed instead on the question of the statistical reality of the ISD population.

2.2. Radar

Ionization generated by an ablating meteoroid acts as a very efficient scatterer of radio waves so that the radar technique permits mass sensitivities orders of magnitude better than achievable by electro-optical methods. The technique is independent of the local weather and has a full diurnal coverage.

Impact ionization is deposited both as a moving plasma sphereoid surrounding the ablating meteoroid body and as electrons and ions in collisional equilibrium with chemical lifetimes of several seconds with a $\sim$ 1m plasma diameter column extending over several kilometers along the track. Consequently there have evolved two techniques for meteor radars: radial geometry – the moving plasma generating head echoes and transverse reflection – taking advantage of the large scattering cross-section from the km long plasma column producing body echoes. In this transverse geometry case the phase summation of scattered radiation (analysed in terms of Fresnel diffraction) restricts observable meteor tracks to those where the reflection is (geometrically) specular: this places tight constraints on the track of a meteor if detectable from three ground stations and therefore delineates a unique trajectory.

The radial method employs a single (usually large paraboloid transmit-receive) antenna that targets the moving plasma ball. With the advent of large aperture radar systems operating at VHF to UHF frequencies (100 MHz to 1 GHz) for other uses, such as military or space debris sensing, they are a valuable tool for sensing Earth impacting dust. This is because some of these specialised radars have the capability of measuring the position of the target in the antenna beam on a pulse by pulse basis and are therefore able to measure the angle of the meteoroid track to the beam axis of the radar and hence velocity components. This velocity history is a valuable feature of the radial technique since it allows a good ($\sim 0.1\mathrm{kms}^{-1}$) estimate of the meteoroid pre-entry speed. This precision is achieved in such specialised radars by employing a system of multiple (usually four) receiving antenna horns displaced from the central focus of the paraboloid dish to provide directional splitting of the overall radiation pattern. Simultaneous signal measurements on the subbeams then provide the angle of the target to the beam axis (monopulse system) to an accuracy of $\sim 0.1°$. The value of the off-axis track – the aspect angle extends up to tens of degrees and arises from the wide cone of scatter from the plasma ball (head echo). Track angle sensing is important since the assumption of an aspect angle of zero (strictly radial to the line of sight) will not only result in large radiant errors and large underestimates of the system collecting area but also in apparent large decelerations – an effect resulting from the changing target angle from the antenna axis.

2.2.1. Radial Geometry

ALTAIR Radar

The ALTAIR (Advanced Research Projects Agency Long Range tracking and Instrument Radar, Kwajalein, Marshall Islands 167.5° E, 9.4°N) dual frequency facility 46 m parabolic dish operates at VHF 160 MHz (beam width

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2.8° and UHF 422 MHz (1.1°) [9]. Meteor head echo data were secured during the Leonid shower epoch 1998. The radar antenna pointing direction tracked the Leonid radiant while for selected periods the radar beam was steered $\sim 40^\circ$ off the radiant direction. Fig 1 demonstrates the wide range of measured trajectory angles to the beam axis (aspect angle). Fig 1 upper when the radar beam was pointing at the Leonid radiant (geocentric ecliptic $\lambda \sim 145^\circ$, $\beta \sim 10^\circ$) situated close to the Earth's apex. Fig 1 lower, the peak at $\sim 35^\circ$ simply reflects the fact that the Leonids and the Earth's apex source were $\sim 40^\circ$ off axis.

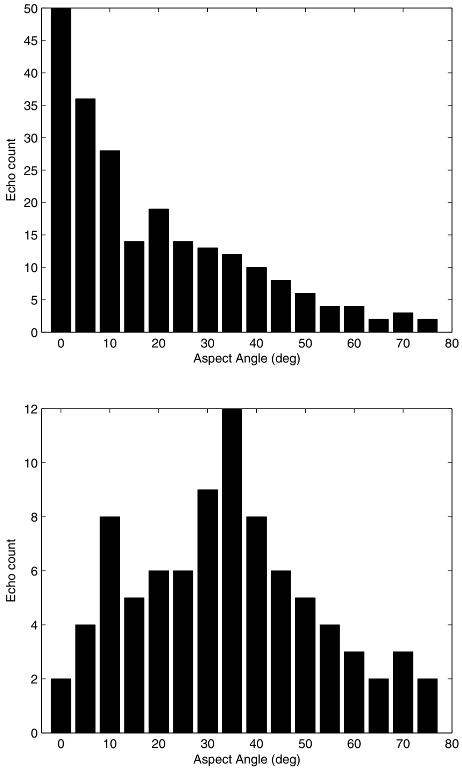

Figure 1. ALTAIR radar Aspect angles UHF echoes. Upper - Leonids 1998 beam pointing to Leonid radiant ($\lambda \sim 145^\circ$, $\beta \sim 10^\circ$) (210 meteors); lower - antenna beam pointing displaced by $\sim 40^\circ$ from Leonid radiant (70 meteors).

The monopulse signal time sequence were reduced to show, for 7 examples, the deceleration with altitude in Fig. 2. The power of the technique is evident: it is clear from the curves that a good estimate of the pre-atmospheric speed can be made. This is a clear advantage of the radial technique. The data for 273 UHF head echo tracks were reduced employing rotation of the Earth, atmospheric deceleration, energy change in the Earth's gravitational field and Earth's orbital motion to yield heliocentric ecliptic velocity components and so provide heliocentric orbits of which 9.5% are unbound.

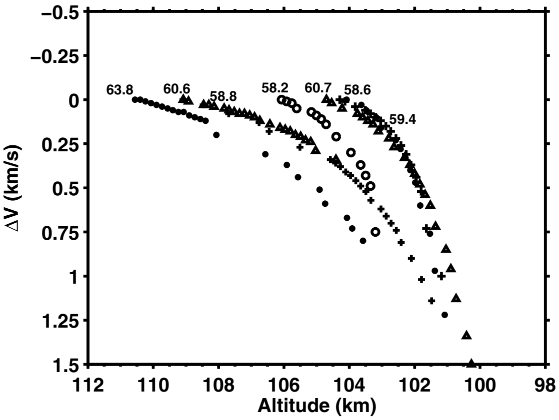

Figure 2. Examples of seven echoes velocity change with altitude. ΔV is change in speed. For each meteor the speed at commencement of echo record (beam entry) is labelled.

TIRA Radar

The Tracking and Imaging Radar operated by FGAN and situated near Bonn, Germany at 7.1°E, 50.6°N is a 35 m parabolic reflector in a radome and operates at 1.33 GHz. The facility was operated during the Leonid epoch Nov 17/18 1999 and also a background calibration period Nov 27 2001. An example of a target track through the antenna beam is given in [10].

Fig 3 show aspect angle distributions for Leonid and background data sets. In contrast to ALTAIR observations the TIRA beam for all data always followed the Leonid radiant coordinates so that for the background day (lower panel) the beam pointed near the Earth's apex – a pointing direction that ensured maximum flux and maximum average velocity as for the Leonid period. Using 400 tracks heliocentric orbits were derived for these meteors. Fig. 4 shows heliocentric speeds for the periods of Leonid epoch and background days. For the upper panel $\sim$8% are open orbits and lower panel $\sim$4%.

In order to fix the inflow directions with respect to the Sun it is necessary to deduce the far-Sun velocity vector. In order to compare closed orbits and open orbit patterns we calculate the far-sun inflow direction as parallel to an ellipse apse line for closed orbits and as along the hyperbolic asymptote for open orbits.

Fig. 5 shows inflow directions in heliocentric ecliptic coordinates with the vernal equinox at centre. The restricted pattern distributions are a result of the data collected over a very limited ($\sim$24 h) period of the year but serve to indicate the proportion of open orbits and the widespread inflow directions: there is no evidence from the small data set of any localised source. The Leonid mean orbit aphelion direction is at ecliptic 241.9°, -2.3°.

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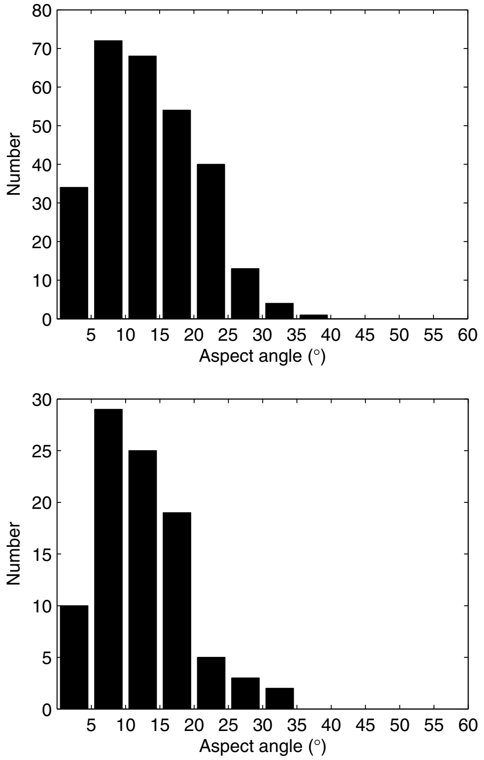

Figure 3. TIRA radar Aspect angles: antenna beam pointing at Leonid radiant coordinates. Upper - Leonids epoch Nov 17-18 1999. Lower - background epoch Nov 27 2001.

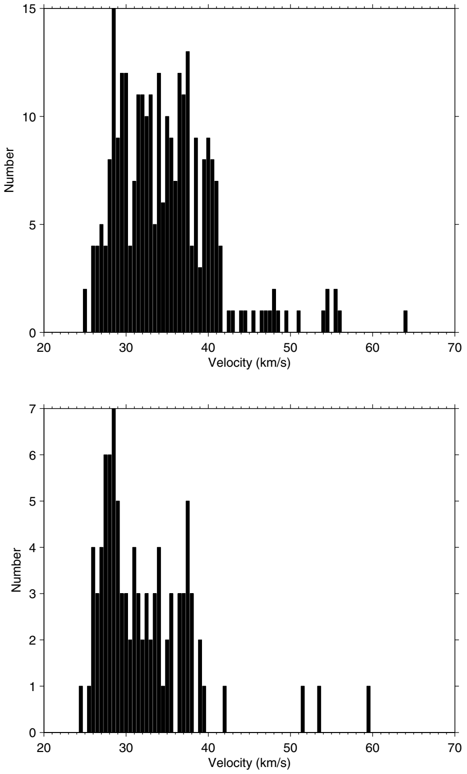

Figure 4. TIRA radar heliocentric speeds V_h (42 kms^{-1} is parabolic limit). Upper - Leonids epoch Nov 17-18 1999. Lower - background epoch Nov 27 2001.

MU Radar

The technique employed by the 46.5 MHz MU (Middle and Upper atmosphere) Doppler radar in Japan employes a two dimensional array of a total of 475 individual Yagi driven elements phased to produce rapid scanning steering of the 3.6° beam. Head echoes were obtained Nov 23 and 24 2000 with the beam pointing at the Earth's apex. An optical-radar study yielded atmospheric incident speed distributions with a clear population ($\sim$6% of the 1393 echoes obtained) in excess of the Earth impact speed limit (73 kms^{-1}) corresponding to the parabolic limit [11].

2.2.2. Transverse Geometry

AMOR Radar

This Advanced Meteor Orbit Radar multi-site facility in New Zealand has a limiting meteoroid mass 3×10^{-7} g and angular orbital accuracy of $\sim 3°$. The system employs $\sim$ 8 km spaced receiving antennas to provide time-of-flight speeds which together with an interferometrically measured echo elevation provides the atmospheric velocity components and trajectory. The meteor scalar speed was also independently measured by the meteor phase record. Designed for continuous operation the system has archived $\sim 10^6$ orbits to map the geometry of the solar system dust cloud [12], to reveal a general solar external dust inflow [13] and depict specific sources. Geometrical evidence on the basis of the seasonal cyclic variation in measured orbital elements [14] and energy patterns in the population of discrete source ([15],[16]) indicated a colinear external inflow of ISD. Extensions to the facility in order to enhance the orbit accuracy to $\sim 0.1°$ are being implemented to provide more precise mapping of ISD.

CMOR Radar

The Canadian Meteor Orbit Radar recently established also employs a transverse reflection method and uses a technique similar to the AMOR system though less sensitive because of lower transmitter power and wider antenna patterns. The broad directional coverage of the system provides an all sky capture system with limiting sensitivity $\sim 10^{-6}$ g [17]. This facility also designed for continuous operation should provide an excellent tool for searching for larger ISD particles.

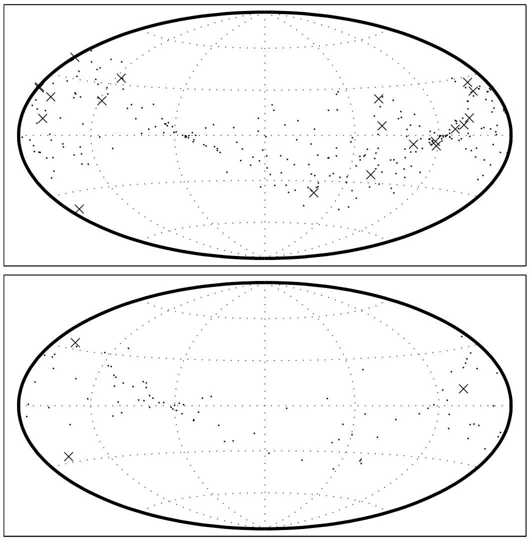

Figure 5. TIRA radar far-Sun upstream inflow directions. Coordinates heliocentric ecliptic: vernal equinox in center, λ increases to the left, β vertical North ecliptic pole at top. Points $(\cdot)$ - closed orbits, crosses $(\times)$ open orbits. Upper - Leonids epoch Nov 17-18 1999. Lower - non-Leonid epoch Nov 27 2001.

3. DISCUSSION AND CONCLUSIONS

The radial radar data available though very meagre and therefore insufficient to allow for ISD mapping, show the important potential of these tracking instruments. The radar systems described above have quite different sky coverage and therefore different radiant and orbital selectivity. There are two aspects that need consideration.

The precission tracking available from ALTAIR and TIRA radars can be compromized by meteor plasma targets occuring in antenna sidelobes. A small fraction of echoes attributed to the main lobe pointing direction will actually be located in antenna sidelobes. Short-lived meteor echoes cannot be assigned to the correct lobe. The cumulative echo detection rate is proportional (dependent on the exact value of the mass distribution index) to the limiting electron line density of the system and therefore on the antenna power gain. For ALTAIR: 1st sidelobe angle 1.5° echo rate contribution 1.7% and velocity error 0.03%; 2nd lobe angle 2.5° echo contribution 0.4% and velocity error 0.9%. For TIRA the corresponding values are 1st side-lobe 0.7°, contribution 1.7%, error 0.007%; 2nd side-lobe 1.1°, 0.04% and error 0.02%. All these outer lobe echo rate contributions (which would result in only small velocity errors) are small compared with the measured unbound orbit rate of $\sim$ 8%.

The pointing direction of the radars (determined by the Leonid meteor stream radiant) in the short campaigns described were near the Earth's Apex encompassing therefore a sample selected to have high Earth impact speeds. This selectivity will enhance the contribution of high geocentric speed meteors and therefore hyperbolics - though the exact bias introduced (compared with the more all-sky transverse geometry radars) is not straightforward to access. However the very limited survey by the specialized high power radars offers proof of concept for interstellar detection.

Ground based sensing of meteors via dual-site modern electro-optical methods operated not only by professional institutions but via the campaigns by the many amateur groups devoted to orbit work should provide valuable data in the future. The large aperture steerable radars with their precise trajectory capability are potentially valuable instruments to delineate sources of ISD: gaining access to meteor records similar to the those data sets provided during the Leonid campaigns of recent years would be very valuable. The transverse geometry facilities while having the advantage of providing good data bases (the AMOR and CMOR archiving $\sim 3.10^3$ orbits daily) should explore ways of extending their trajectory accuracy from a few degrees to fractions of a degree to ensure better mapping resolution. For comparison the planned DUNE (Dust Near Earth) mission has a directional resolution $\sim 1°$ [18]. It is the precision in dynamics and their large databases where the ground-based meteor sensing methods can well complement the presently more coarse directional *in situ* measurements.

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